An Inexpensive Distance Measuring System for Location of Robotic Vehicles

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Abstract

An distance-measuring system based on a swept frequency reflectometer radar system was built and tested for application to navigation of robotic vehicles in a sealed room where GPS signals are not available. The final system built en masse would cost approximately $25. The system was simulated using HP/EEsof (Libra) software and tested using inexpensive commercial components. Several signal processing methods were compared for deriving distance from the data acquired from the system. Log periodic antennas (LPA) were used to test the system, and inexpensive LPA and Yagi-Uda microstrip patch arrays were built and tested for use in this application.

Introduction --The Swept Frequency Reflectometer

The distance measuring system is shown in Figure 1. The transmitted signal is swept over a given bandwidth, and the signal is reflected back after it encounters a discontinuity. The superposition of the reflected and the transmitted waves forms a standing wave at the mixer that can be used to find the distance traveled by the transmitted signal.

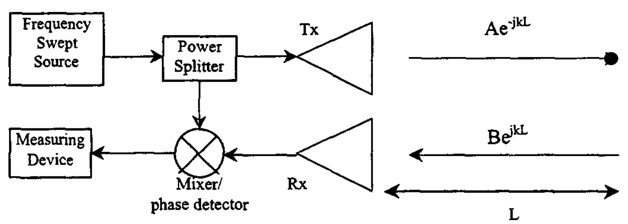

Figure 1 : Swept Frequency Reflectometer distance measuring system

A balanced mixer used as a phase detector is a square law device that outputs power directly proportional to the squared magnitude of the received voltage. This forms a one dimensional standing wave pattern [1]. The magnitude at the output of the mixer is a standing wave proportional to cos(2kL). As the transmitted signal is swept over a range of frequencies, each different frequency (different values of k) gives a different phase change and hence mixer output, each proportional to cos(2kL). Plotting the mixer output as a function of frequency gives the cos(2kL) waveform that is proportional to the distance (L) being measured. The Fourier Transform of this waveform in the spatial (L) domain will give a Dirac delta function at the distance being measured.

Range and Resolution

The range (Lmax) and resolution (ΔL) of the system are determined by the frequency range and number of frequencies swept through the system. To get an accurate FFT, a minimum of one cycle of sinusoidal waveform is required. Hence this will determine the resolution (ΔL) given by

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$$\Delta L = \frac{u}{2\Delta f}$$

where u is the velocity of propagation (3e8 m/s if the medium is air and approximately 2e8 m/s for cables), $\Delta f = f_2 - f_1$, where f_2 is the stop frequency, and f_1 is the start frequency of the sweep. Figure 2 shows a plot of resolution (ΔL) vs. frequency sweep bandwidth (Δf). The marked value is the one used in this application. The Nyquist Criterion determines the range of the system, Lmax. As the source frequency is swept between start frequency f_1 and stop frequency f_2, the frequency is incremented in a fixed step size "stepincr", giving a fixed set of output points. This is equivalent to sampling the output at a particular rate.

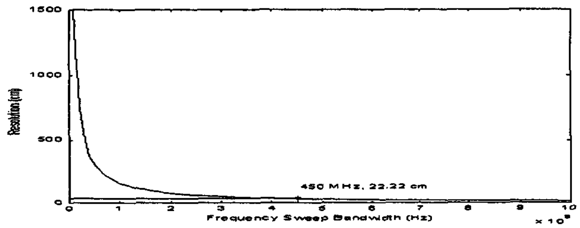

Figure 2:Resolution vs. Frequency Sweep Bandwidth

The range of the system is found from

$$L\max = \frac{u}{4stepincr}$$

and is shown in Figure 3. The implication of these range and resolution calculations is that they are independent of a start (f_1) and a stop (f_2) frequency. For this application the range was 5m, the resolution 22 cm, using a frequency range of 800 MHz – 1250 MHz.

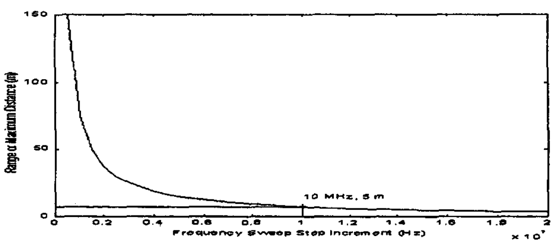

Figure 3: Range vs. Frequency Sweep Step Increment

Methods of Data Processing

The waveform at the output of the mixer is a sine wave with a DC offset, where the frequency of the sine wave is the frequency of the current swept frequency step. The DC offset as a function of frequency (ie. k) will be cos (2kL). It is necessary to use some form of data processing to obtain the value of L. Fourier transformation is an obvious choice, but several other methods were also compared. These include:

1. Fourier transform with no interpolation
2. Fourier transform with either linear interpolation
3. Zero-crossing detection
4. Mathematical modeling of the sine wave

The first three data-processing methods are straight-forward applications of standard methods found in any signal processing textbook. The mathematical modeling method is based on modeling the sinusoidal data mathematically. The expected data is sinusoidal in nature

$$x(n) = A\cos(\omega n + \theta) \tag{1}$$

and can be modeled as a linear mathematical model.

$$x(n) + a_1 x(n-1) + a_2 x(n-2) = 0 \tag{2}$$

This linear difference equation has coefficients, a_1 and a_2, which are unknown. There are just two unknowns in the equation and many different values of x(n). Thus a matrix equation can be formed, and the difference equation can be solved.

$$\begin{bmatrix} x[2] & x[1] \\ x[3] & x[2] \\ x[4] & x[3] \\ \dots & \dots \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = -\begin{bmatrix} x[0] \\ x[1] \\ x[2] \\ \dots \end{bmatrix} \tag{3}$$

The values of a_1 and a_2 obtained from (3) can be substituted in (2) and then solved for x(n). The solution of (2) has a characteristic equation (4).

$$z^2 + a_1 z + a_2 = 0 \tag{4}$$

The roots of the above equation are complex conjugates, and since the data is sinusoidal, they lie on a circle with unit magnitude. The angle of any one of the roots will directly give the frequency relative to the sampling frequency. A complete circle represents the sampling frequency, so the root r_2 represents half the sampling frequency. The drawback of this method is that its accuracy is reduced if the data set is noisy.

Results and Conclusions

The system performance and performance of the various signal processing methods was first tested by measuring the lengths of cables. This was done first using the HP/EESOF simulation software, to analyze the effects of circuit limitations in a noise-free environment. This eliminated any errors from environmental clutter, multipath, imperfect reflections, and antenna losses or mismatches. For this case, all methods provided excellent results for cable length prediction, with error less than 5%. The mathematical modeling method was best. The circuit was then built and tested, and Table 1 shows the performance of the different signal processing techniques for data analysis of experimental data on cables. The FFT method of processing works well for all cases tested (simulation and experimental). It can be improved on slightly by linear interpolation. The mathematical modeling method gives excellent result for simulated data, which is noise-free, however its accuracy is reduced in experimental data that has some noise.

The system was then tested for realistic distance-to-the-wall measurements. The system was placed facing a metal wall (originally in a screen room to remove environmental clutter and later in an ordinary lab room facing the back of a metal bookcase.) Two LPA antennas from Tempest, Inc. were used as the RX and TX antennas. The results from these tests are shown in Table 2. Both the FFT and mathematical model methods were shown to work well, and the system is sufficiently accurate to measure distances of up to 5m with error less than 5%. It should be noted that the total "distance" is twice the distance to the wall, since the wave must travel twice this distance before returning to the receiver. This system is being implemented in a robotic vehicle to maintain its orientation for navigation in shielded metal spaces by determining the distance to three fixed walls on either side and in front of it. Inexpensive microstrip Yagi-Uda and LPA arrays are being used for the final design. A second implementation, presently under development, is to separate the receiver and transmitter so that the vehicle can determine its distance from a known base station.

Table 1 Comparison of signal processing techniques for analysis of experimental data on cables

ACTUAL LENGTH (cm)	FFT Method (cm)	Math. Modeling (cm)	FFT w/ Interpolation (cm)	Zero Crossing (cm)
40	49.83	56.06	50.8	44.46
61.595	68.39	73.36	66.44	64.36
75.692	81.09	90.1	82.07	80.386
122.7	129.94	135.45	128.97	131.72
182.88	193.45	197.22	191.5	194.57
250.825	264.77	265.8	265.75	270.124
441.96	454.32	454.68	453.35	457.46

Table 2 -- Experimental Results for distance-to-wall measurement using LPA antennas as RX and TX

ACTUAL LENGTH (cm)	FFT (cm)	Mathematical Model (cm)
38	44	46.3
64	68.8	64.1
98	109.2	100
124	145.1	133
154	172.9	165.3
184	197.56	185.3

REFERENCES

[1] D.A. Noon, "A computer-controlled microwave distance measuring system," Bachelor of Electrical Engineering (Honours) Thesis, Univ. of Queensland, AU, 1991